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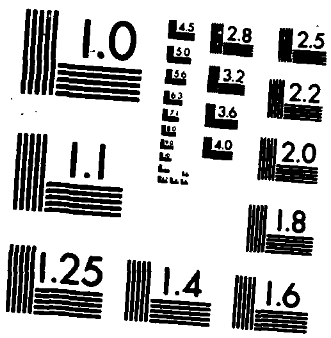

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for

AFOSR - 83 - 0002

STUDIES OF THE AURORAL ZONE IONOSPHERE USING THE MITHRAS DATA BASE

Fiscal Years 1983 - 1985

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1.) High-Latitude Electrodynamics: Ionospheric response to substorms at widely separated local times was investigated using simultaneous data from the three participating radars.

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7.) Thermosphere and Exosphere: The diurnal variation of exospheric temperature over 30 degrees of latitude around Millstone Hill has been investigated using MITHRAS elevation scan data. The effects of frictional heating due to ion-neutral collisions have been studied.

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Dr. J. E. Salah (total support from MIT funds)

7. JUNIOR RESEARCH PERSONNEL:
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9. ABSTRACT OF OBJECTIVES AND ACCOMPLISHMENTS:

The extensive MITHRAS radar data set collected under AFOSR support at Millstone Hill, Chatanika, and EISCAT during 1981 - 1983 was the object of extensive analyses which addressed the processes and characteristics of the auroral-latitude ionosphere and thermosphere. Automated data retrieval techniques and the use of multi-instrument data sets were emphasized. This research program at Millstone Hill incorporated multi-national collaboration involving both experimentalists and theoreticians in a variety of investigations which included the following activities.

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INTRODUCTION

During 1981 and 1982 the Atmospheric Science group at the MIT Haystack Observatory Millstone Hill Radar participated in the AFOSR supported multi-radar MITHRAS experimental campaign (de la Beaujardiere et al., 1984). Coordinated observations of the Earth's ionosphere, magnetosphere, and thermosphere were conducted using the Millstone Hill, Massachusetts, Chatanika, Alaska, and European EISCAT incoherent scatter radars in conjunction with a variety of ground based and satellite experiments. Chatanika and EISCAT are about 11 hours apart in magnetic local time, and Millstone Hill precedes Chatanika and follows EISCAT by more than 6 hours ~~(Figure 1)~~. Each of the three radars was able to study auroral zone latitudes, but at widely spaced longitudes. Hence the MITHRAS program was well suited to study the class of problems which involve universal time/local time ambiguities, or equivalently, space/time differences. Set operating modes were used at the radar sites to best match the requirements of the several campaign objectives. The overall MITHRAS program was motivated by a desire to provide a well documented set of radar observations of the mid and high latitude ionosphere during the brief interval when three incoherent scatter facilities would be available. At Millstone Hill the MITHRAS program involved the development of specific radar operating modes and analysis techniques appropriate for multi-instrument studies. An extensive data set resulted from the campaign.

RESEARCH ACTIVITIES AND ANALYSIS PROJECTS

The Massachusetts Institute of Technology Haystack Observatory Atmospheric Sciences group participated in a three-year program of investigations of the auroral ionosphere concentrating on the analysis of the MITHRAS and related radar data sets. This research was directed toward gaining abroad understanding of ionospheric phenomena and processes at high latitudes by exploiting the unique characteristics of the multi-instrument MITHRAS data set. This report summarizes the areas of investigation pursued and highlights the results of those studies.

1. High-Latitude Electrodynamics:

An important MITHRAS goal has been to clarify the spatial/temporal response of the ionosphere to impulsive phenomena including magnetospheric substorms and their effects on the large-scale ionospheric structure and characteristics. The preliminary co-operative work of de la Beaujardiere et al.(1983) intercompared simultaneous electric field observations made at the radars in order to investigate the signature of an individual substorm at widely spaced locations. This study concluded that the ionospheric electric field signature of a substorm is a function of the local time, independent of the longitude of the station. In the dawn and dusk sectors the electric field is intensified, whereas around noon and midnight the electric field

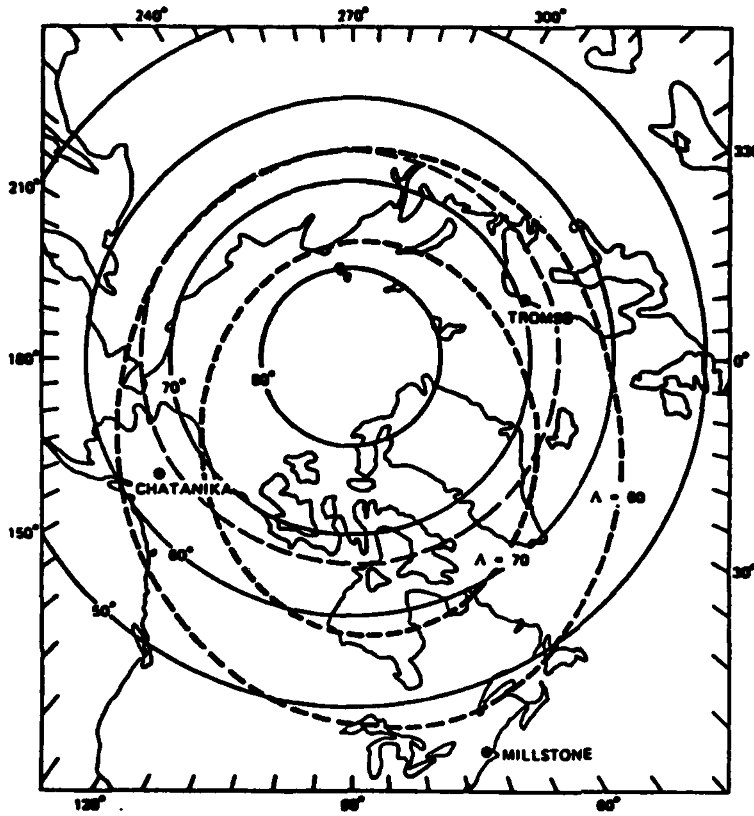


Fig. 1. Map showing the location of the three MITHRAS radars at Chatanika, Alaska, Millstone Hill, Massachusetts, and EISCAT in Scandanavia.

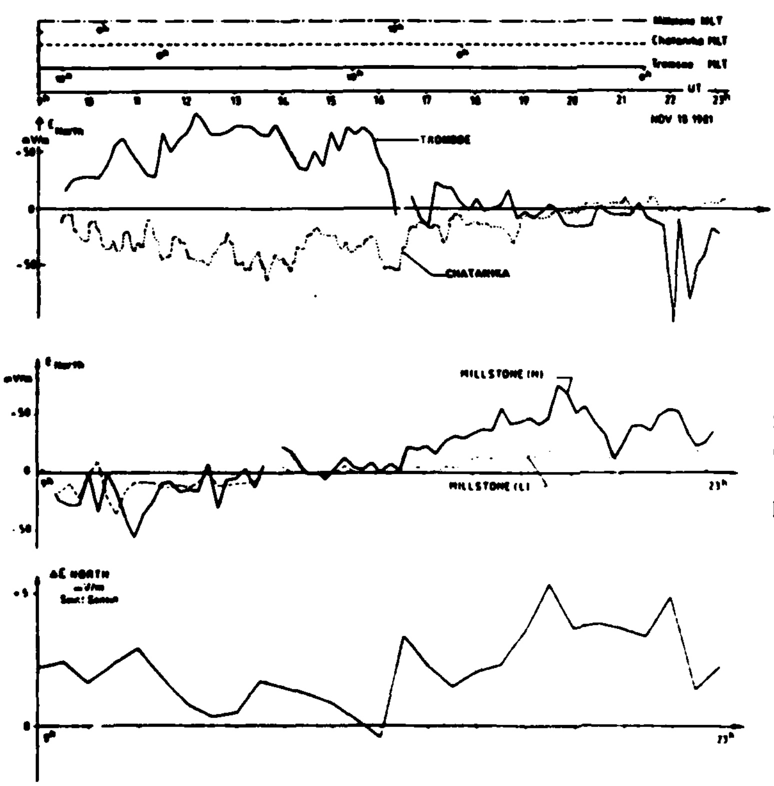


Fig. 2. Comparison of the northward electric field components at Tromsoe (EISCAT), Chatanika, Millstone Hill, and the French radar at St. Santin (after Caudal et al.,1984).

appears to reverse during a substorm. A similar study was undertaken by the French EISCAT group which concentrated on data from the three MITHRAS incoherent scatter radars, the French radar at St. Santin, and the STARE radar on 11 Nov., 1981. Figure 2, taken from Caudal et al. (1984), compares the electric fields at these sites during a period when the radars observed the dusk, dawn, and midnight regions simultaneously. This study exemplifies the international collaboration which has been a major part of all aspects of the MITHRAS program.

2. Ionospheric Plasma Transport:
A portion of the Millstone Hill scientific effort was directed towards better understanding ionospheric plasma structure and dynamics at mid and high latitudes. Studies of plasma transport received added emphasis because of the elevated high-latitude F-region densities which characterized the recent solar cycle maximum (a period which included the MITHRAS radar campaign). Because of its sub-auroral location the Millstone Hill radar is optimally situated for investigating ionospheric processes associated with the formation of the mid-latitude trough. Several trough production mechanisms have been examined in detail. Solar eclipse data were used to quantify the temporal and spatial extent of trough formed during a known decrease in the level of ionizing radiation (Holt et al., 1984a). The interplay of corotation and convection in the formation of the trough in the evening sector were investigated by Holt et al. (1983). The possibility that the trough is formed by rapid convection of low density plasma from the night sector or increased charge exchange during periods of enhanced convection was discussed by Evans et al. (1983) who suggested that a fossil trough remains to mark the location and extent of that disturbance.

The impulsive intensification of the electric field during substorms is accompanied by its equatorward penetration into the region of high plasma density on the equatorward edge of the evening sector trough. This results in the bulk transport of solar-produced F region plasma towards the dayside ionospheric cleft where it can be swept poleward into the polar cap. The work of Foster (1984) describes the features of plasma transport from the sunlit dayside ionosphere, through the noon sector cleft, and across the polar cap to the darkened winter midnight sector (Figure 3). High plasma densities were used as a tracer of the cross-polar cap convection pattern. The investigation of de la Beaujardiere et al.(1984) examined the universal time dependence of nighttime F region densities at high latitudes (Figure 4). Data from the longitudinally spaced MITHRAS radars on 18-19 Nov., 1981 and 15-16 Dec., 1981 were used to demonstrate that when the cusp region of plasma entry into the polar cap is sunlit, the plasma density in the midnight sector is enhanced. Cross polar cap transport from the dayside to midnight is responsible for this phenomenon. The characteristics of these MITHRAS observations were used in model simulations conducted by Sojka and Schunk (1985, 1986) to investigate the mechanisms involved. It was concluded that electric field transport

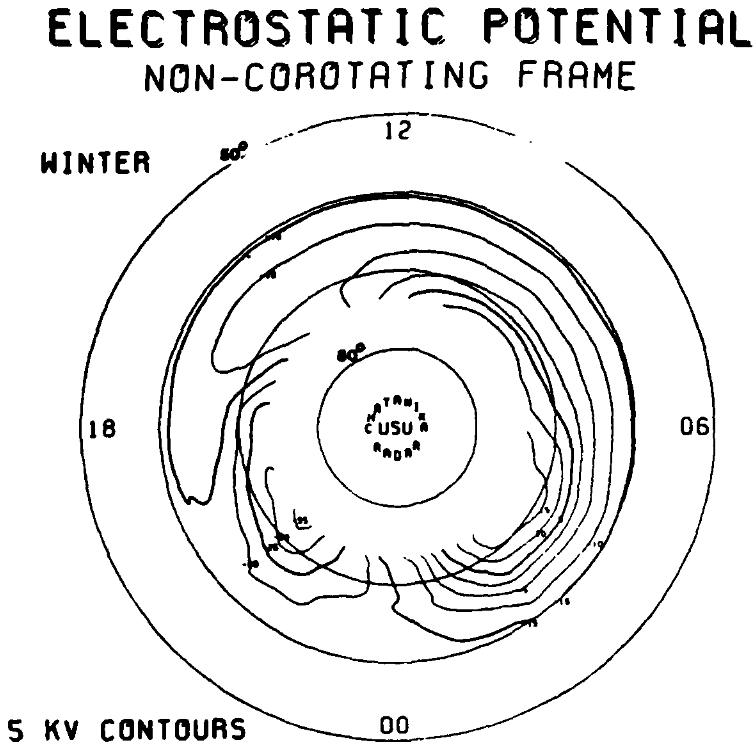
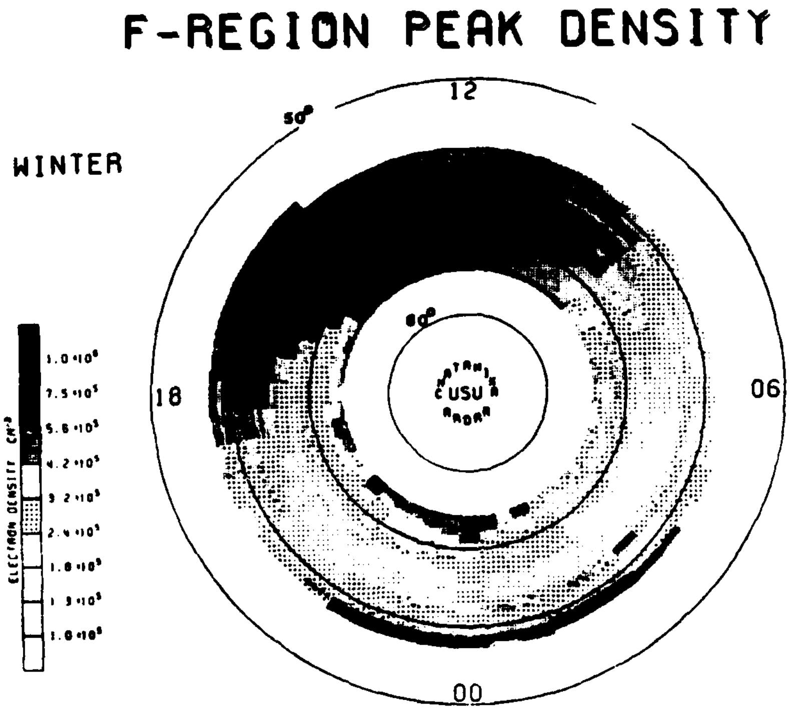


Fig 3. Empirical model contours of electrostatic potential (convection streamlines) observed during winter experiments at Chatanika (Foster, 1984).



Average F-region peak densities corresponding to convection pattern above. Plasma transport by convection into (out of) the polar cap on the dayside (nightside) is indicated by the radar observations.

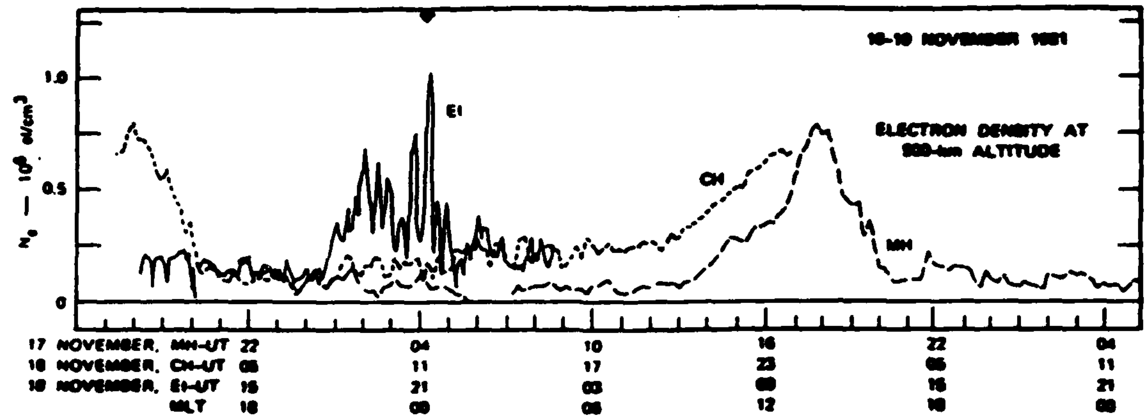
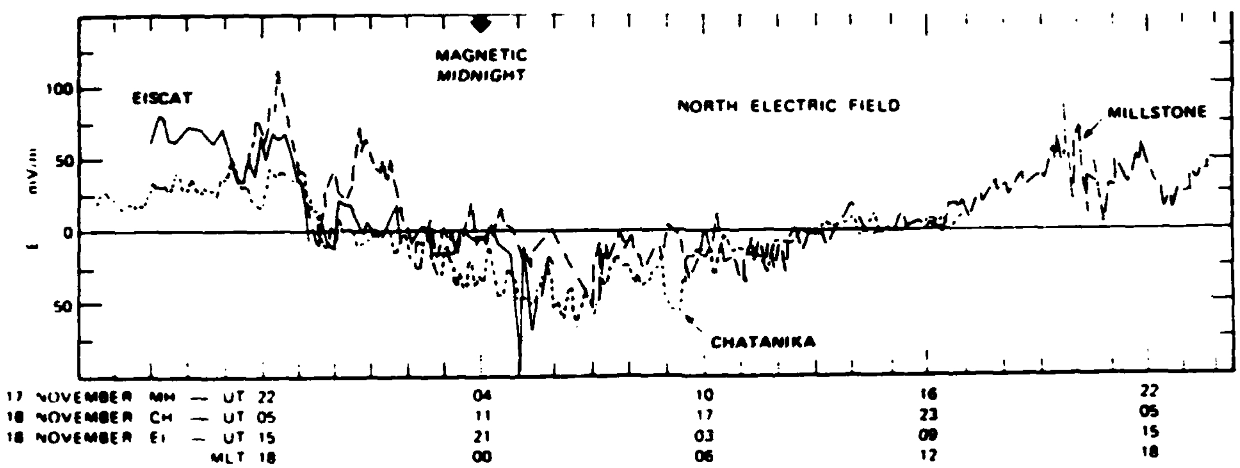


Fig 4. Diurnal variation of plasma densities observed by three MITHRAS radars plotted as a function of magnetic local time. Nighttime densities observed on EISCAT's longitude greatly exceed those observed at the other sites (after de la Beaujardiere et al., 1985).



Northward electric field components observed at the three radars.

contributes strongly to the occurrence of high density plasmas, and the resultant ionospheric irregularities, at polar latitudes.

3. Convection Snapshots:
Multi-station measurements are able to make a particularly strong contribution to studies of high latitude convection. Measurements of plasma convection at high latitudes have been made by ground based incoherent scatter radars (Holt et al., 1984b), by coherent scatter radars, and by plasma drift or electric field detectors on satellites. The field of view of a single instrument or facility cannot encompass the entire high-latitude convection pattern. Multi-instrument studies utilizing simultaneous data from a number of sites were a major goal of the MITHRAS experimental program. Fortunately radar and satellite measurements are to a considerable extent complementary, and by combining data from several satellites and ground-based instruments substantial progress can be made toward determining the instantaneous global convection pattern at a given universal time. The MITHRAS observations, in particular, are well suited to studies of the shape of the convection pattern.

Details of the near-instantaneous convection pattern during the course of a moderately disturbed day have been examined with radar and satellite data by Heelis et al.(1983). The Millstone Hill MITHRAS data are used in such studies to provide both broad local time and latitude coverage of the convection pattern. Figure 5 is taken from the Heelis paper and demonstrates the synthesis of a large portion of the high-latitude electrostatic convection potential pattern from the simultaneous multi-site observations. Similarly, a latitudinal array of observatories monitors to equatorward expansion of the convection electric field during auroral disturbances. The study of Gonzales et al. (1983) assembled data from a latitudinal chain of stations and has led to further investigations of the data acquired at low latitudes during the MITHRAS period.

4. Comparisons with Models:
The ability of the radar observations to quantify ionospheric parameters has been used in a series of comparisons of the MITHRAS observations with ionospheric models. These multi-radar/model case studies have had the goal of identifying the roles played by competing processes, thereby improving the detailed ionospheric predictive capability of the models. These model studies have been directed towards reproducing large-scale ionospheric features and their diurnal and activity variation, and include satellite as well as radar data as inputs. The work of Sojka et al.(1983), which examined the effects of high latitude plasma transport, concentrated only on data from the Millstone Hill site. This study indicated the necessity of incorporating realistic descriptions of the convection electric field and of auroral particle precipitation in predictive models. Subsequent studies have extended the comparison to multi-site data. Figure 6, taken from Rassmussen et al. (1986), compares the model predictions (solid line) of ionospheric density with the values observed at Millstone Hill over the course of a summer

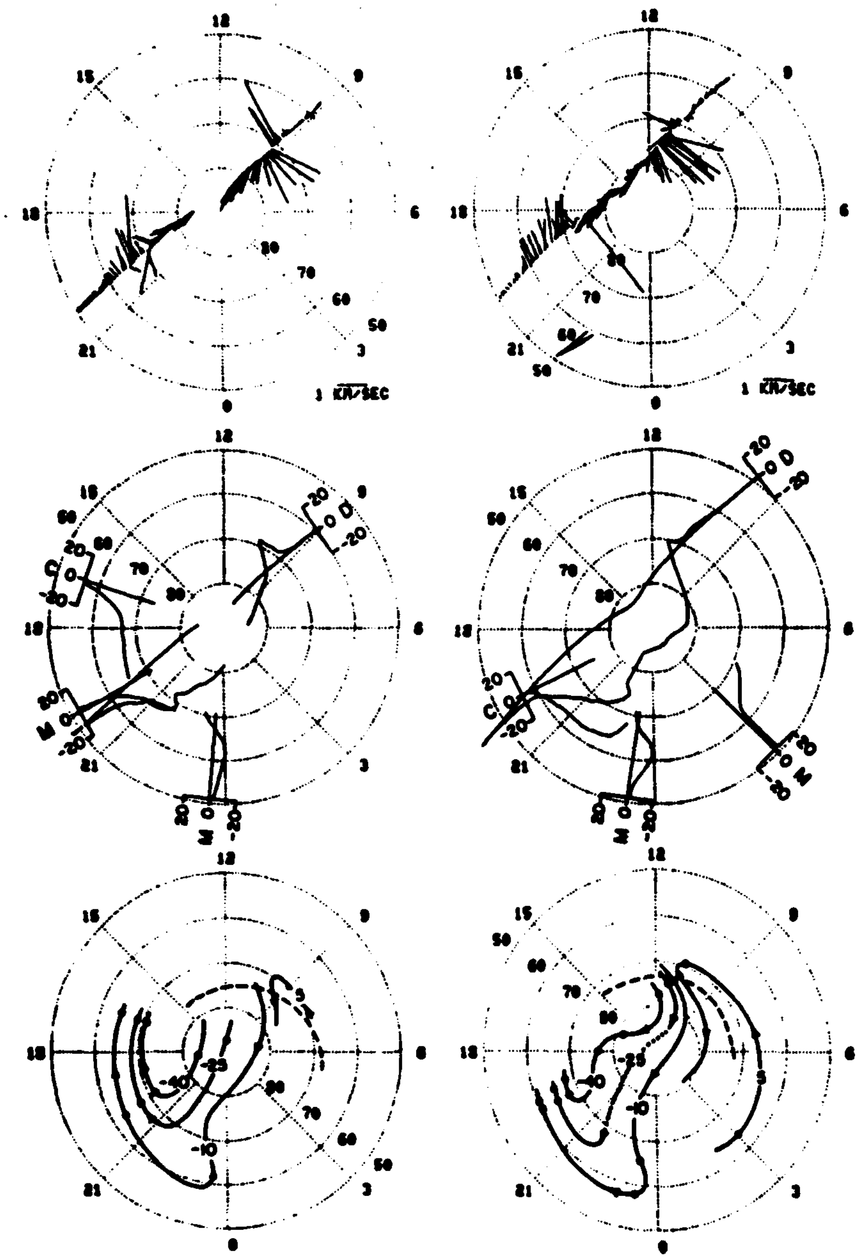


Fig. 5. Composite high-latitude convection pattern derived from simultaneous MITHRAS radar observations at Millstone Hill and Chatanika and DE satellite overpass. Near snapshots of the convection pattern were obtained by this multi-technique approach (after Heelis et al., 1984).

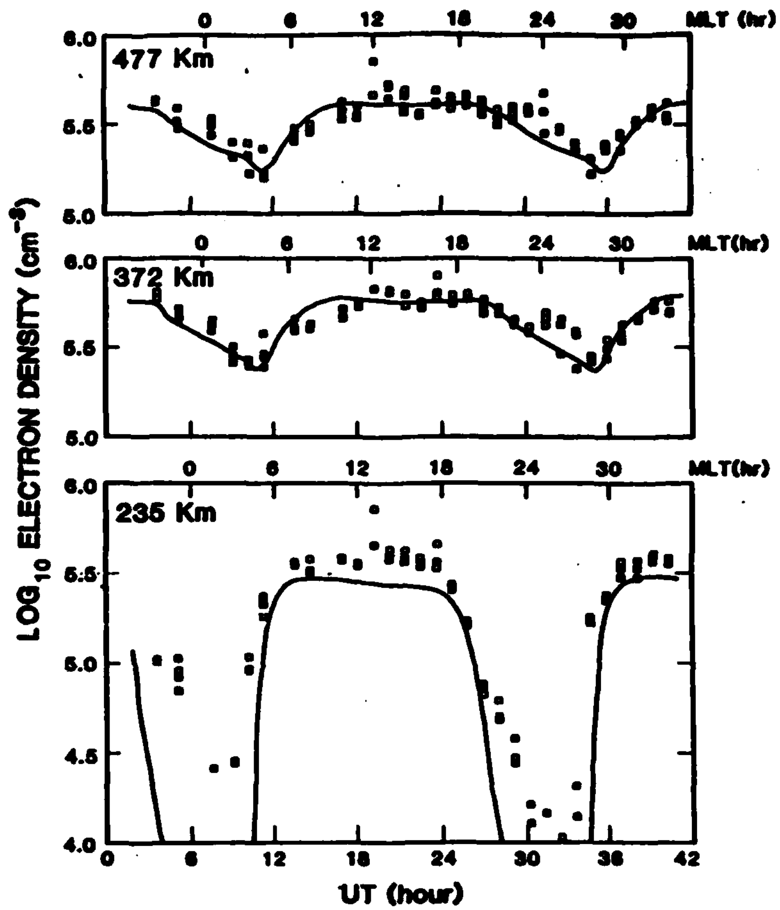


Fig 6. Comparison of Millstone Hill observations of the diurnal variation of plasma density at three altitudes with the predictions of a theoretical ionospheric model (after Rassmussen et al., 1986).

day. The model used in this study incorporated the features of the convection patterns observed at the two sites and was adjusted to fit the Millstone Hill and Chatanika data simultaneously. Electron temperatures at the two sites are being investigated in an extension of this latter study. As detailed in Section 3 above, additional modeling work of Sojka and Schunk (1985, 1986) has been directed towards explaining the characteristics of high-latitude plasma transport observed during the MITHRAS experiments.

In other studies the MITHRAS data have been used to refine various aspects of ionospheric models by providing a basis for more precise analytical representations of high-latitude phenomena. Analysis of a large body of Millstone Hill data has led to changes in the Volland-Stern convection model to better represent the coupled magnetosphere - ionosphere system. These changes enable the models to better represent the diurnal variation of the convection potential along Millstone Hill's longitude. Characteristic parameters of the models can be determined by direct comparison with the extensive MITHRAS data. An examination of the Volland-Stern latitudinal decay constant, gamma, indicates a value between 1 and 2 is appropriate for conditions when the cross polar cap potential is 30 kV.

5. Data Base Studies and Empirical Models:
Large amounts of ionospheric data are acquired during each incoherent scatter experiment. A major contribution of the MITHRAS analysis effort at Millstone Hill has been the development of an extensive database capability to store and access the observations taken at the different sites throughout the campaign. In cooperation with the work done at SRII, data exchange formats were developed to facilitate the use of multi-facility data in programs which can access and analyze any data provided in the common format. At Millstone Hill the availability of the MITHRAS data set in this common format led to the development of analysis programs specifically designed to use this large volume of data. Graphics display techniques were developed to facilitate the intercomparison of data from the different sites and for comparisons with theoretical predictions. Empirical models of high-latitude convection and plasma parameters were generated as a part of this effort and have been expanded to incorporate additional types of data gathered during the MITHRAS experiments. The empirical models supplement the analytic theoretical models and provide an apt benchmark for their development.

During the proposal period the range of data accessible through the data base system has been enhanced in three major ways. First, the MSIS model neutral atmosphere has been added. As a result, model neutral densities are always available in conjunction with any measurements. This capability has greatly facilitated thermospheric studies, which usually depend on the availability of neutral atmosphere parameters. Second, the system now is capable of directly accommodating data in the NCAR data base format. As a result, data from all incoherent scatter stations are available just as if they had been collected with the Millstone Radar. This substantially enhances the utility of the system for multi-instrument studies, since many of the computer programs and analysis techniques developed for Millstone data may immediately be applied to data from other instruments. Third, hourly IMF and interplanetary plasma parameters from the NASA composite omnitape have been fully incorporated into the Millstone data base system. These parameters are of critical importance for studies of the high-latitude ionosphere because they characterize the solar wind which is an important driving and controlling force for the magnetosphere and high-latitude ionosphere and thermosphere.

The entire data set acquired at Millstone Hill under the MITHRAS program has been incorporated into empirical models which quantify ionospheric features under carefully defined conditions. The interrelationship of particle precipitation at high latitudes and ionospheric convection has been investigated by Foster et al. (1986a) who have prepared models of the convection electric field for increasing levels of the intensity and extent of particle precipitation as quantified by an auroral precipitation index based on direct satellite observations of the high-latitude environment. Directly accessing over 200 days' observations through the Millstone Hill data base, the observed radial (line-of-sight) drifts velocities were sorted into local time bins at 1/2 hour intervals and 2 degree intervals of apex latitude. Since each of these cells had been viewed by the radar over a wide range of aspect angles over the course of the experiments, the true mean drift velocity can be obtained in a statistical sense. This was done by using sequential estimation techniques which were developed at Millstone and allow an almost arbitrarily large number of linear systems to be analyzed in parallel. Equipotential contours of the convection electric field were derived from the average convection velocities. Figure 7 presents the convection models derived from this extensive data set for four levels of particle precipitation. An earlier study investigated the controlling effect of the interplanetary magnetic field on the ionospheric electric field by separating the radar data according to two ranges of Bz and two ranges of By before averaging (Foster et al., 1986b). Such statistical studies are of great importance in determining the details of solar wind - magnetosphere - ionosphere coupling.

The binning technique described above has been designed to be used with multi-instruments data sets. Any measurement of an ion velocity or electric field component may be used since the vector field is being determined in a statistical sense. A critical need is for data over the polar cap, beyond the field of view of the Millstone Hill radar. This type of data is available both from the Sondrestrom incoherent scatter radar and polar orbiting satellites, and we are now beginning to install these polar cap data sets on the Millstone computer. Important new results are expected from this MITHRAS project in the next few years as the Millstone Hill binning techniques are applied to multi-instrument data sets accessed through the Millstone Hill data base system.

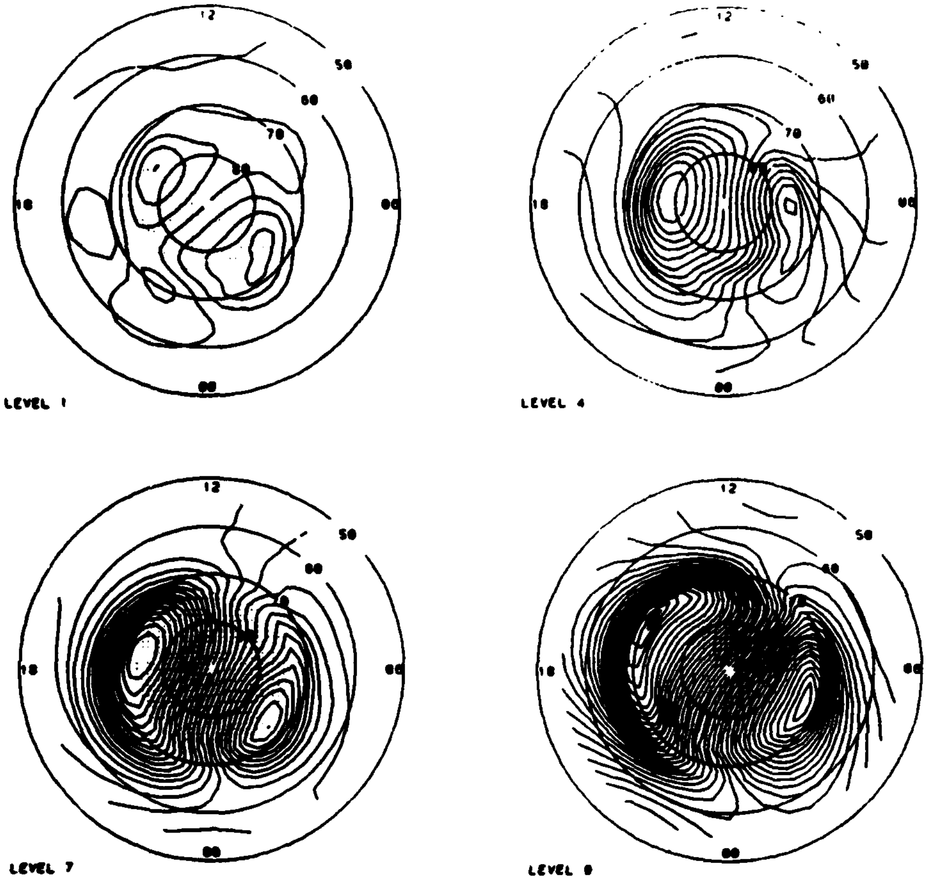


Fig. 7. Empirical analytic models of high-latitude ionospheric convection derived from over 200 days' data in the Millstone Hill data base, for four discrete levels of precipitating particle intensity (after Foster et al., 1986).

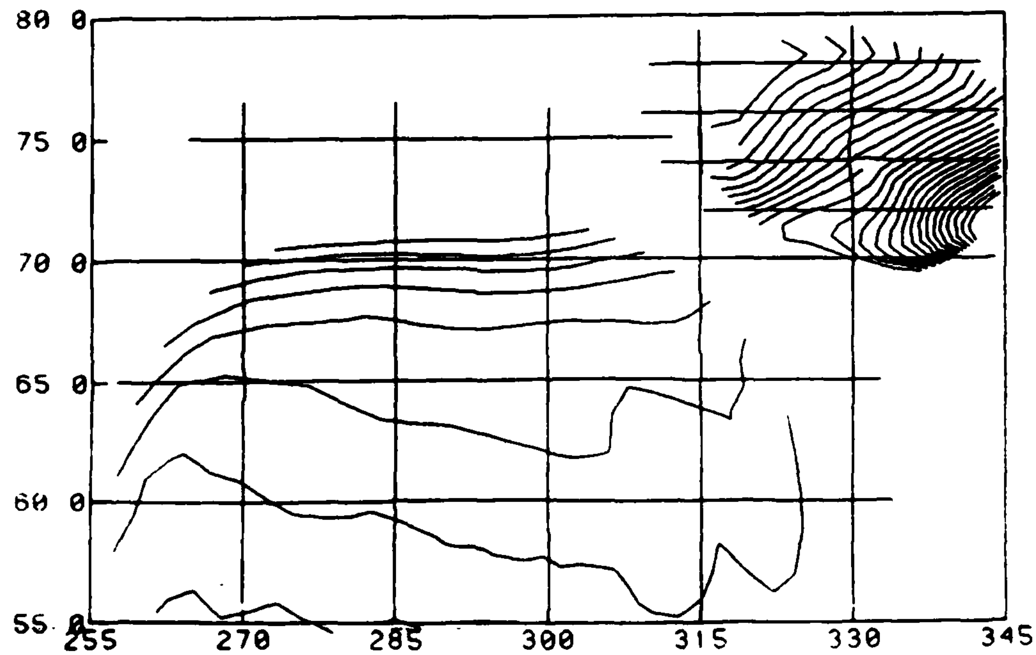


Fig. 8. Potential patterns calculated from simultaneous azimuth scans with the Millstone Hill and Sondrestrom radars on May 16, 1984. This experimental and analysis technique reveals complex details of the convection pattern over a wide extent of local time.

The large amount of data available, and the existing tools to process them, will allow significant progress to be made in resolving the ambiguities in the dependence of the ionospheric convection pattern on geophysical conditions. This information will contribute to the development of improved empirical models based based on a combination ionospheric and geophysical parameters.

6. Azimuth Scanning Experiments:
The azimuth scanning observing mode employed at Millstone Hill during the MITHRAS campaign provides a near snapshot of high latitude ionospheric phenomena. The technique employs "windshield wiper" azimuth scans of the radar antenna from East to North to West which cover a wide range of local times and latitudes with good temporal resolution. These experiments provide spatial maps of F region ionospheric parameters over the 2500 km radius field of view of the 46 meter steerable antenna. Electron densities and plasma temperatures are derived from spectral analysis of the data from a single spatial sampling window while the plasma drift motion and the convection electric field, being vector quantities, must be derived from the line of sight Doppler velocities observed from a number of positions. The azimuth scan experiments used at Millstone Hill are designed to maximize the spatial and temporal resolution of these vector quantities while avoiding the uncertainties which can arise in making measurements in a dynamically changing, spatially inhomogeneous environment. A number of techniques were developed by the Millstone Hill analysis group to derive the convection patterns from the scanning experiments in order to provide high time resolution electric field maps for MITHRAS and other multi-instrument studies. The investigations of Heelis et al. (1983) and Holt et al. (1984a) utilized these techniques to advantage.

The azimuth scan analysis techniques developed under this proposal are being applied to observations taken at other radar sites and in a continuing program of multi-instrument ionospheric studies. Foster et al. (1985) have generated high-resolution convection maps made in the important cleft region of the dayside ionosphere from azimuth scandata taken with the Sondrestrom, Greenland radar. Recently we have succeeded in applying the analysis techniques described above to azimuth scans conducted simultaneously at Millstone and Sondrestrom. An example of a two radar combined potential pattern is shown in Figure 8. The combined field of view of the two radars spans latitudes from the equatorward extent of the auroral sunward convection through the convection reversal and some 8 degrees into the polar cap. Millstone Hill observed the evening sector at dusk while Sondrestrom covered the Harang region near midnight. The continuity between the two patterns is quite good, verifying that the separate boundary conditions used for the two radars yield reasonable and consistent patterns. In areas such as this, the MITHRAS analysis program is being used as the basis for continued investigations of high-latitude phenomena.

7. Studies of the Thermosphere and Exosphere
Elevation scan observations made at Millstone Hill during the MITHRAS experiments have been analyzed to produce local time - latitude maps of exospheric temperature. The work of Oliver (1984) provides data over 30 degrees of geodetic latitude and reveals that while there is a pronounced diurnal variation in the exospheric temperature, there is little latitudinal variability which cannot be accounted for by the influence of frictional ion heating. Baron and Wand (1983) examined frictional heating effects on the ion temperatures observed from Millstone Hill and Chatanika in order to clarify the coupling of high-latitude plasma dynamics to the neutral upper atmosphere. The exospheric temperature data are also being used in tests of the predictive capability of thermospheric models such as the TGCM of R. Roble (NCAR). The work of Oliver et al. (1984) displays the variation of the exospheric temperature as seen in the combined Millstone Hill - Sondrestrom field of view throughout two summer days. Such experiments, and the detailed information they provide on the global high-latitude upper atmosphere, continue on a regular monthly basis and constitute an immediate legacy of the MITHRAS program.

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On the Latitudinal Variations of the Ionospheric Electric Field during Magnetospheric Disturbances, C. A. Gonzales, M. C. Kelley, R. A. Behnke, J. F. Vickrey, J. M. Holt, and R. H. Wand, J. Geophys. Res., 88, 9135, 1983.
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Comparison of model high-latitude electron densities with Millstone Hill observations, J. J. Sojka, R. W. Schunk, J. V. Evans, J. M. Holt, and R. H. Wand, J. Geophys. Res., 88, 7783-7793, 1983.

SCIENTIFIC INTERACTIONS

1. Spoken Papers:

Observations of Convection Electric Fields from Millstone Hill (J. C. Foster and J. V. Evans), Chapman Conference on Magnetospheric Currents, Irvington, Virginia, April, 1983.

Patterns of Magnetospheric Convection derived from Chatanika and Millstone Hill Radar Observations (J. C. Foster, W. L. Oliver, and J. J. Sojka), Spring AGU Meeting, Baltimore, Maryland, June, 1983.

Millstone Hill Studies related to the MITHRAS Program (J. C. Foster), EISCAT Scientific Symposium, Aussios, France, September, 1983.

Multi-radar Studies of the Auroral Ionosphere with the Millstone Hill Radar (J. C. Foster), US-Finland Auroral Workshop, College Park, Maryland, October, 1983.

Studies of the Mid and High-Latitude Ionosphere with the Millstone Hill Radar (J. Foster), National Radio Science Meeting, Boulder Co., January, 1984 (invited).

High Resolution Observations of Electric Fields and F region Plasma Parameters in the Cusp Ionosphere (J. Foster, J. Holt, J. Kelly, and V. Wickwar), NATO Workshop of the Morphology and Dynamics of the Polar Cusp, Lillehamar, Norway, May, 1984.

Atmospheric Science Computer Facilities at Millstone Hill (J. C. Foster), Optical Ground-Based Aeronomy Workshop II, Ann Arbor, Mi., June, 1984 (invited).

High Resolution Observations of the Auroral Oval/Polar Cap Boundary (J. Foster), AGU Chapman Conference on the Magnetospheric Polar Cap, Fairbanks, Ak., August, 1984.

Incoherent Scatter Observations of Ionospheric Electric Fields (J. C. Foster), Fall AGU Meeting, San Francisco, Dec., 1984.

Multi-Radar Mapping of High-Latitude Ionosphere, HILAT Science Symposium (J. Foster), AFGL, January, 1985.

Solar Wind Control of High-Latitude Convection and Precipitation (J. Foster, J. Holt, and R. Musgrove), Chapman Conference on Solar Wind - Magnetosphere Coupling, Cal. Tech., Feb., 1985.

Dynamics of the Terrestrial Ionosphere (J. Foster), IAGA Symposium, Prague, August, 1985.

Ionospheric Characteristics at the Auroral Oval - Polar Cap Boundary (J. Foster), IAGA Symposium, Prague, August, 1985.

2. Consultative Interactions:

July, 1983: AFGL , discussions of HILAT/radar cooperative research

August, 1983: AFGL, symposium presentation on high latitude convection

October, 1983: Boston Univ., symposium presentation on MITHRAS observations

January, 1984: Utah State University, MITHRAS analysis projects

April, 1984: Boston College, seminar on multi-radar studies

January, 1985: AFGL radar / HILAT collaboration

January, 1985: MIT Plasma Physics Symposium presentation on radar

PROFESSIONAL PERSONNEL

During 1983 Dr. J. V. Evans left MIT and the Millstone Hill Radar for a position with the COMSAT Corporation. He was replaced as Principal Investigator on this AFOSR-supported research program by Dr. J. C. Foster. The continuity of the MIT research program has been maintained through the efforts of the Millstone Hill research and support staff and through Dr. Foster's prior involvement in the MITHRAS program at Utah State University.

Dr. John C. Foster - Principal Investigator (May - Oct., 1983)
Dr. John V. Evans - Principal Investigator (Oct., 1982 - April, 1983)
Dr. R. H. Wand
Dr. G. B. Loriot
Dr. J. M. Holt (no direct financial support)
Dr. W. L. Oliver (no direct financial support)
Dr. J. E. Salah (total support from MIT funds)
Mr. C. del Pozo - MIT graduate research assistant

Travel Supported by AFOSR MITHRAS Project

April, 1983 Washington, D. C.: J. Foster, to confer with AFOSR

May, 1983 Baltimore, Md.: J. Foster, to attend Spring AGU meeting (paper on MITHRAS results presented)

June, 1983 Plymouth, N. H.: J. Foster, to attend Gordon Conference

September, 1983 Aussois, France: J. Foster, partial support to attend EISCAT Scientific Symposium and MITHRAS working group meeting (invited MITHRAS review paper presented)

September, 1983 Aussois, France: C. del Pozo, partial support to attend EISCAT Scientific Symposium

February, 1983 Boulder, Co.: J. Holt and W. Oliver attended the MITHRAS meeting and NSF/NCAR Data Base Workshop under NSF support

January, 1984 Boulder, Co.: J. Foster, to attend URSI National Meeting (MITHRAS results presented in invited review paper).

February, 1984 Washington, D.C.: J. Foster, to attend URSI/IS Radar working group meeting (conferred with AFOSR and attended MITHRAS analysis sessions).

August, 1984 Fairbanks, Ak.: J. Foster, to attend AGU Chapman Conference on Magnetospheric Polar Cap (presented paper on multi-radar experiment analysis).

September, 1984 Florence, Italy: C. del Pozo, partial support to attend International URSI Meeting.

December, 1984 San Francisco, Ca. J. Foster to attend Fall Meeting of AGU (presented paper on electric field observations).

February, 1985 Pasadena, Ca., J. Foster to attend Chapman COnference on Solar Wind - Magnetosphere Coupling (presented paper on empirical electric field modeling).

May, 1985 Baltimore, Md., J. Foster to discuss multi-radar analyses and to attend Spring Meeting of AGU.

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